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COMPARISON BETWEEN SPECTRAL SCANNING THEORY AND CLASSICAL COLOR VISION THEORIES

By

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1. INTRODUCTION

This memorandum compares the Spectral Scanning theory[1] with the classical theories of color vision. There is no one detailed theory of color vision that has general acceptance, but nevertheless there is nearly universal agreement in the basic principle of the receptor mechanism set forth by Thomas Young in 1801. A generalized statement of Young's postulate is that color vision is achieved by the signals generated in at least three different types of photosensitive elements with different spectral absorption responses. Essentially all theories of the receptor mechanism of color vision have been built on this principle. Most of these theories have assumed three different types of photosensitive elements, which was what Thomas Young believed, and are together referred to by the loosely defined term Trichromatic theory. Today the Trichromatic theory has very wide acceptance and so will be used as a standard of comparison for the Speetral Scanning theory.

The present status of the Trichromatic theory can be summarized as follows:

(1) There is no direct physiological evidence to substantiate the Trichromatic Theory.

(2) The primary indirect evidence represents (a) color-mixture psychophysical measurements, and (b) fairly recent spectrophotometer measurements of the retina, which was initiated by Rushton.

(3) There are a great many contradictory psychophysical phenomena that the Trichromatic theory has not been able to explain satisfactorally.

Up to now there has been no alternative to the Thomas Young principle that has provided what has generally considered to be a plausible explanation of the receptor mechanism of color vision. This appears to be the main reason for the widespread belief in the Trichromatic theory, despite the theory's many limitations.

In comparison, the following can be said relative to the Spectral Scanning theory:

(1) The theory provides an explanation of color mixture psychophysical measurements which is at least as satisfactory as the Trichromatic theory.

(2) There is a high degree of consistency between the Spectral Scanning theory and psychophysical measurements in general. The author has not found any important contradiction between a psychophysical measurement and the Spectral Scanning theory.

(3) Re-evaluation of the spectrophotometer measurements of the retina by Rushton and others shows that these measurements are also consistent with the waveguide mode postulate of the Spectral Scanning theory. This data definitely does not prove the existence either of different types of pigments or different types of cones, as has been frequently assumed.

(4) There already exists qualitative physiological evidence substantiating the Spectral Scanning theory in the waveguide mode effects known to exist in the outer segments of the cones, whereas there is no direct physiological evidence substantiating the Trichromatic theory. With further study of the waveguide mode patterns, it should soon be possible to provide quantitative agreement between color mixture experiments and the actual waveguide mode patterns in the receptors.

Considering that the Spectral Scanning theory is less than a year old, the evidence in its favor is remarkably great.

The most important implication of the Spectral Scanning theory is the explanation it gives of chromatic adaptation, which is described in Reference (6). The theory leads to the conclusion that chromatic adaptation is performed in terms of multi-dimensional spectral patterns represented by the spatial energy distributions in the photodetector region and by the modulated waveforms. This is in direct contrast with the classical concept that chromatic adaptation is performed in terms of three-dimensional trichromatic signals. By implementing chromatic adaptation in this manner, a visual system based on the Spectral Scanning theory could provide extremely accurate spectral discrimination over great changes in level and chromaticity of the illuminant by means of natural feedback effects. In contrast, it appears very doubtful that anything approaching the spectral discrimination and adaptation capabilities of human vision could be built on the principle of the Trichromatic theory.

The Spectral Scanning theory opens up a great many new approaches for research in human vision, which include in particular the following:

(1) A new approach to chromatic adaptation. The theory predicts that visual adaptation is multi-dimensional and so raises serious questions concerning the adequacy of our conventional three-dimensional color-matching experiments for studying visual adaptation.

(2) A theoretical basis for definition of uniform color space. The proposed mechanism for the detection and adaptation processes of the receptors should provide the basis for a theoretical model of a uniform color space that could be very valuable in color standardization work.

(3) Study of waveguide modes in receptors. The theory predicts the basic manner in which the shapes of waveguide modes in the outer segments of the cones are related to color mixture data. Thus a very clear direction for study of waveguide mode effects is indicated.

(4) Study of flicker phenomena. The theory should provide a theoretical basis for explaining the complicated flicker fusion and Fechner color phenomena.

These represent just a few of the multitude of new areas of vision research in which the Spectral Scanning theory can provide a new direction of thinking.

This memorandum presents a detailed comparison of experimental evidence relative to the Spectral Scanning theory and the Trichromatic theory, and shows that the Spectral Scanning theory is at least as consistent with this evidence as the Trichromatic theory. A preliminary examination of the energy distributions produced by waveguide mode effects is made, and shows what appears to be the basis for agreement between waveguide mode patterns and color mixture data. As a supplement to this memorandum, Reference (6) gives a detailed discussion of visual adaptation relative to the Spectral Scanning theory.

2. RELATING WAVEGUIDE MODE PATTERNS TO COLOR MIXTURE DATA

The Spectra Scanning theory[1] postulated that the spatial distributions of energy across the cone for different wavelengths are produced be waveguide mode effects. However, no direct relation was shown between waveguide mode patterns and the spatial energy distributions predicted in the theory. The following discussion gives preliminary evidence for such a relationship.

The outer segments of the cones are shown by Enoch[2] to act as cylindrical dielectric waveguides. Snitzer[3] shows that the spatial energy distribution of a single mode in a cylindrical waveguide has circular symmetry about the axis of the cylinder, with a radial dependence proportional to the square of a Bessel function.

Figure 1 gives plots of the square of the first three Bessel functions. At low optical frequencies, only the mode corresponding to the zeroth-order Bessel function can propogate. As the frequency is increased (or the wavelength is decreased) the cutoff frequencies for higher modes are exceeded, and higher order modes that produce energy distributions defined by higher order Bessel functions can propogate. Thus we might expect that in the red wavelength region the J_0 distribution would predominate, in the green region the J_1 distribution would predominate, and in the blue region the J_3 distribution would predominate, as is indicated in Figure 1.

The exact parameters of the possible waveguide mode patterns are very difficult to calculate even when the waveguide characteristics are accurately established. The probem is further

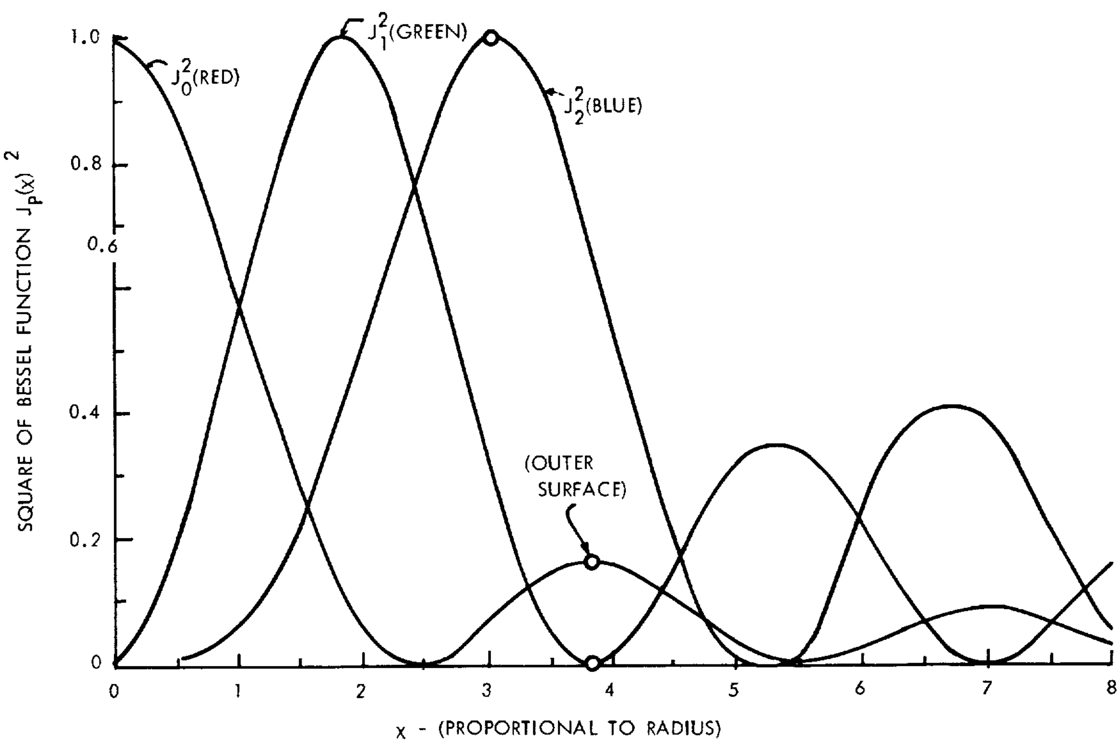

Figure 1. Squares of First Three Bessel Functions Showing Possible Relation to Wavelength Discrimination Effects

complicated by our lack of accurate knowledge of the dielectric characteristics of the receptors. Consequently, the following discussion will merely try to show qualitative relationships between waveguide mode patterns and the spatial energy distributions predicted in the Spectral Scanning theory. These qualitative relationships should be useful in pointing the way in which more intensive research on the waveguide mode effects in the receptors should progress.

Compare the Bessel function plots of Figure 1 with the calculated energy distributions across the cone for the Spectral Scanning theory given in Figure 10 of Reference (1). There is a great deal of similarity if we assume that Position 1.0 of the energy distribution plot (Figure 10 of Reference 1) represents the axis of the outer segment of the receptor and Position 0 represents the outer surface, Thus it appears that the variable "Position on Cone" approximately represents the relative radial distance measured from the outer surface. In the Bessel function plots of Figure 1, circles are drawn corresponding to the value of X at the outer surface of the receptor which give good agreement between the Bessel function plots and the predicted energy distributions of the theory. We are interested in the portions of the Bessel function plots for values of X up to the circled points.

The spatial energy distributions for deep blue (470mμ) and violet (445mμ) in Figure 10 of Reference (1) show anomalous humps in the region of Position 0.5. These probably are merely due to the assumptions made in the analysis. By assuming different demodulation approaches and changing certain assumptions, the anomalous humps can be eliminated.

There is enough similarity between the Bessel function plots and the calculated spectral energy distributions of the theory to indicate the possibility of a relationship between them. The spatial energy distributions for the theory can be varied somewhat by assuming different demodulation process, and the Bessel function plots can be varied somewhat by assuming different detailed electromagnetic characteristics in the outer segment. Thus there is flexibility to account for discrepancies, but not so much flexibility that clear conclusions can not be drawn from the comparison.

From a knowledge of the gross dielectric characteristics of the outer segments of the cones we can determine the patterns of permissable waveguide modes. However, the actual mode patterns that do propogate may be determined by the ultra-microstructure of the outer segments. For example, a possible waveguide mode could be eliminated by means of infinitesmal discontinuities in the outer segment which provide high impedance paths for the circulating currents associated with that mode.

3. STANDARD OF COMPARISON FOR SPECTRAL SCANNING FOR THEORY

In 1801 Thomas Young proposed in essence that the neurological signals for color vision are derived from three different types of photosensitive elements* having different spectral absorption curves. This principle forms what is now generally called the Trichromatic theory.

Hundreds of theories of color vision have been built on this basic principle of Thomas Young. Most of them have assumed three types of photosensitive elements and so are Trichromatic theories. However some have assumed four or more types of photosensitive elements. Since this extension of the concept of Thomas Young to include more than three photosensitive elements does not represent a significant change of concept, we should consider all these theories as merely variations of the Thomas Young theory, even though they may not be Trichromatic theories.

*The author has avoided the use of the common term "receptor," and has instead used the more precise term "photosensitive element". A single cone is a receptor but could contain three different photosensitive elements.

It is nearly universally believed today that the receptor mechanism must operate in accordance with the basic concept of Thomas Young. There is almost as great agreement that there are only three photosensitive elements, or in other words that the Trichromatic theory is correct.

The main reasons why there is such a strong belief that there can be only three photosensitive elements are as follows:

(1) Since only three spectral responses are necessary, the use of more would represent useless redundancy.

(2) If the color vision process has more than three independent channels of information, one cannot explain constancy of three-dimensional metameric matches. The assumption for explaining constancy of metameric matches is that two matching spectra evoke the same responses from each of the three spectral absorption curves, and so will always match regardless of the processing of the signals from the signals from the three absorption curves. If there are more than three independent spectral absorption curves, the signal processing for the separate channels must be inter-related in some complicated manner as yet unexplained.

The requirement of the Trichromatic theory for three different spectral absorption curves does not necessarily demand three different types of cones. The three absorption curves could be defined by three different photopigments arranged in different mixtures in four or more cones. The important requirement is that there be only three independent spectral absorption curves, which mathematically is equivalent to stating that the optical detection process must be three dimensional.

Thus we see that, if we accept the basic principle of Thomas Young, we appear to be forced to accept the same asumption he made, i.e., that there are only three different spectral absorption curves. We are forced to accept the Trichromatic theory, which demands that the optical detection process be three dimensional.

In contrast, the Spectral Scanning theory proposes that a scanning process generates the spectral information, which is processed in a single channel. This theory leads to the conclusion that the detection process has a dimensionality much greater than three and that chromatic adaptation is performed in terms of this multi-dimensional information. Constancy of metameric matches is satisfied to the accuracy with which they really hold merely by requiring that the single channel be approximately linear.

From a practical point of view, if we are to compare the Spectral Scanning theory with other theories of color vision, we should limit the comparison to the Trichromatic theory because (1) the Trichromatic theory is nearly universally accepted, and (2) there are so many detailed theories of color vision it is virtually impossible to consider them all. Besides, the author has not been able to find any theory that proposes a plausible explanation of the receptor mechanism of color vision that is not based on the Thomas Young Principle. The essential difference between the Trichromatic theory and the Spectral Scanning theory is that the Trichromatic theory demands that the photopic optical detection mechanism be three dimensional whereas the Spectral Scanning theory demands that it generates a neurological signal of much higher dimensionality.

4. EXPERIMENTAL EVIDENCE

4.1 Basis for Confidence in Trichromatic Theory

The general acceptance of the Trichromatic theory in the field of color vision might lead one to think that it must be well substantiated by experimental data. However, this is not the case. The primary reason for its general acceptance seems to be that there has not been any good alternative.

Balaraman[4] has presented a historical review of color vision and the Trichromatic theory in a recent issue of the Psychological

Bulletin (Harry Helson, Editor). His concluding statement is as follows:

> "After more than a century of scientific research in color vision, the Trichromatic theory continues to face theoretical contradictions and unexplained facts. Trichromatic theorists everywhere should rigorously examine the theory's basic assumptions, provide much more experimental data on the basic visual functions, and honestly ask themselves the question, should the theory be subject to drastic revision or should it be replaced by some other theory?"

Let us compare the Trichromatic theory and Spectral Scanning theory in terms of how well they satisfy the experimental evidence.

4.2 Microscopic Evidence

Marriott[5] has recently summarized the microscopic evidence for the Trichromatic theory as follows:

> "So far, microscopic studies have revealed no differences in (the) structure or pigmentation (of the cones) that could be concerned with colour vision, and theories about different pigments and different types of receptor are based only on indirect evidence."

In a later section entitled "Experimental Basis for Theory," Marriott says:

> "The Trichromatic theory is based primarily on the facts of colour matching and provides a simple and convincing explanation of the trivariance of normal color vision. Rushton's identification of the foveal pigments is strong confirmation of the theory."

Marriott goes on to discuss other psychophysical data, but more in the line of explaining contradictions rather than giving solid support for the Trichromatic theory. Thus it appears that that the above statement defines what Marriott feels is the major evidence for the Trichromatic theory.

Although there is no microscopic evidence for the Trichromatic theory there is microscopic evidence for the waveguide mode effects postulated in the Spectral Scanning theory.

The dimensions and chemical characteristics are such that waveguide modes can be propagated. From a first approximation the theoretical mode patterns appear to be consistent with the energy distributions required in the theory. Enoch[2] has observed waveguide mode patterns that are qualitatively consistent with the Spectral Scanning theory.

On the other hand, an important problem in reconciling Enoch's microscopic observations with the Spectral Scanning theory is that the waveguide mode patterns Enoch observed for individual receptors show a great variability. This could be due to the effects of bleaching or damage to the retina in this measurements. In Enoch's measurements the retina is nearly completely bleached. A redeeming feature in this regard is that the adaptive effect of differential bleaching in the receptors under normal operation would tend to offset the effects of differences in waveguide patterns from cone to cone, just as it compensates for the effects of a changing illiminant spectrum.

4.3 Pschophysical Evidence

The primary evidence for the Trichromatic theory arose from the psychophysical data of color mixture. However this same data is also consistent with the Spectral Scanning theory and so cannot be used as a basis for comparing the two theories.

In the last few years Hurvich and Jameson have presented a great deal of psychophysical data to substantiate the opponent-process principle of the Hering theory. This is in direct agreement with the Spectral Scanning theory. However, one can also reconcile the Hering theory with the Trichromatic theory by postulating appropriate processing of the neurological information.

There have been many attempts to deduce the three primary spectral sensitivity curves of the Trichromatic theory from psychophysical experiments, but these efforts have been continually unsuccessful. Many different sets of curves have been derived by making different assumptions, but no one set has been proved to be unique.

As Balaraman has pointed out, there is a large amount of psychophysical evidence that presents serious questions to the Trichromatic theory. However one can build on the basic Trichromatic theory an infinite variety of postulates to explain detailed contradictions that arise from the data. Consequently it has as yet not been possible to conclusively disprove the basic Trichromatic theory by the psychophysical data.

The Spectral Scanning theory appears to satisfy the major psychophysical data at least qualitatively in a very natural manner. However this body of information is quite large and considerable research is required to achieve a detailed comparison of the theory with this data.

In the author's judgement the Spectral Scanning theory provides a considerably more parsimonious explanation of psychophysical data than does the Trichromatic theory. However the question of parsimony (regardless of how strong) involves value judgements that are difficult to defend against the hard forces of tradition.

This does not mean that it will be impossible to decide between the Spectral Scanning theory and the Trichromatic theory on the basis of psychophysical data. There is a very clear psychophysical point of difference between the theories. The Trichromatic theory contends that chromatic adaptation is definable by a three dimensional transformation, whereas the Spectral Scanning theory maintains that that transformation is performed in terms of data of a much higher dimensionality. Appropriate psychophysical research should be able to use this point of difference as a basis for designing crucial experiments to decide between the two theories.

4.4 Electrophysiological Measurements

Measurements of electrical signals within the retina have supplied very strong evidence to substantiate the Hering theory.

The S-potentials originally measured by Svaetichin give responses as functions of wavelength which have the same shape as the spectral responses of the white-black, blue-yellow, and green-red opponent processes of the Hering theory.

A number of years ago Granit measured from the impulses in the optic nerve the responses of a number of spectral response curves, which led to the postulate of the polychromatic Dominator-Modulator theory by Granit. However the more recent discovery of the S-potentials by Svaetichin has indicated that Granit was probably measuring the peaks of the Hering-type opponent process signals and not the responses of spectral absorption curves.

Thus we can say that the electrophysiological experiments have given strong substantiation to the Hering theory but they cast little light on the validity of the Trichromatic theory.

A-C modulation signals have been measured in the retina, which is in agreement with the Spectral Scanning theory, but does not prove the theory's validity.

4.5 Chemistry of Visual Pigments

Work on the chemistry of the visual pigments has given very strong evidence to show that there is only one visual pigment in the cones, iodopsin, which has a spectral absorption curve that nearly matches the photoic luminosity curve of the eye. Discrepancies are easily explainable in terms of (1) macular pigmentation and (2) efficiency of transmission of different wavelengths down the outer segments of the cones.

This evidence is in direct agreement with the Spectral Scanning theory and offers serious difficulties to many versions of the Trichromatic theory. The usual belief by Trichromatic theorists is that the three spectral absorption curves are determined by the absorption curves of different photopigments. These theorists generally reject the strong evidence on the chemistry of the visual pigments by maintaining that there is still a possibility that two other pigments exist in the cones, which have not yet been found.

4.6 Spectrophotometer Data

The only area where clear experimental evidence appears to exist to substantiate the Trichromatic theory is that of spectrophotometer measurements of the retina, work that was initiated by Rushton. Rushton compared the reflectivity spectrum of the retina before and after bleaching with various wavelengths and from this data was able to derive the spectral responses of what appeared to be a "green" and "red" pigment. He was unable to determine the response of a "blue" pigment, presumably because the reflectivity in the blue region was so low the effect of the "blue" pigment was lost in the noise of the experiment.

Rushton could not be sure from these experiments whether he was measuring the absorption spectra of different pigments or the response of one pigment and different filter effects. To answer this question he and Brindley shone lights of various wavelength through the sclera of the eye which reached the cones from a direction opposite to normal. Rushton found that the subject matched this light with roughly the same wavelength of a light in the normal direction. Rushton concluded from this experiment that filter effects could not be important in the color sensation and therefore his spectrophotometer measurements must be detecting different photopigments.

It is important to note, however, that Rushton's two pigments appear to act like a single pigment chemically, because he found that they regenerate at exactly the same rate. There is also a serious problem of reconciling this multiple pigment hypothesis with the failure of the chemical analysis to isolate the two pigments Rushton has appeared to find.

Let us examine Rushton's results in terms of the Spectral Scanning theory. The theory proposes that waveguide mode effects in the outer segments of the cones produce different spatial distributions of energy for different wavelengths. Consequently bleaching with different wavelengths would produce different spatial patterns of bleached pigment across the cone. This would result in different spectral absorption curves as a function of the wavelength of bleaching, which is in agreement with Rushton's spectrophotometer measurements. The two spectral response peaks measured by Rushton could well be the effect of first and second order waveguide modes.

Rushton's experiment of shining the light throughthe sclera merely indicates that the waveguide mode effect to consider should be independent of the direction of transmission of light through the outer segment. We thus would conclude that the spatial variation of energy produced by the waveguide mode has a simple radial dependence, which is what one would have expected. The same basic waveguide mode patterns can be excited regardless of the direction of the light through the outer segment of the cone.

Thus we see that at least in a qualitative sense Rushton's experiments do not conflict with the Spectral Scanning theory. Further work on the waveguide mode effects is needed to prove quantitative agreement.

Micro-spectrophotometer measurements of the outer segments of individual cones in crushed fish retina have been made by William Marks at Johns Hopkins University, which have appeared to indicate the presence of three different types of cones with peak spectral responses in the red, green, and blue regions. However one can interpret this result in terms of the Spectral Scanning theory by assuming that for some reason different waveguide modes are accentuated in different cones. This may be due to such effects as the difference in angle with which the light hits the outer segment, the state of preadaption of the cones, the chemical characteristics of the region that surrounds the cone, mechanical effects on the cones of crushing the retina, etc.

These micro-spectrophotometer measurements of the cones are of course extremely significant. However there is good reason to believe that with proper research they can be reconciled with the waveguide-mode postulate of the Spectral Scanning theory.

5. Conclusions Concerning Experimental Evidence

When we evaluate the experimental evidence objectively we must accept the conclusion that the Spectral Scanning theory is in at least as good agreement with the evidence as the Trichromatic theory. There do not appear to be any areas where serious contradiction exist that could necessitate large changes in the premises of the Spectral Scanning theory. However there is great need for research into many areas to provide detailed evaluation of the theory in terms of the experimental data.

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